Technical Report CERC-96-5
September 1996

US Army Corps of Engineers
Waterways Experiment Station

Periodic Inspection of Nawiliwili Harbor Breakwater, Kauai, Hawaii

Report 1
Base Conditions

by *Robert R. Bottin, WES*
Stanley J. Boc, Pacific Ocean Division

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Prepared for Headquarters, U.S. Army Corps of Engineers

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Report 1 of a series

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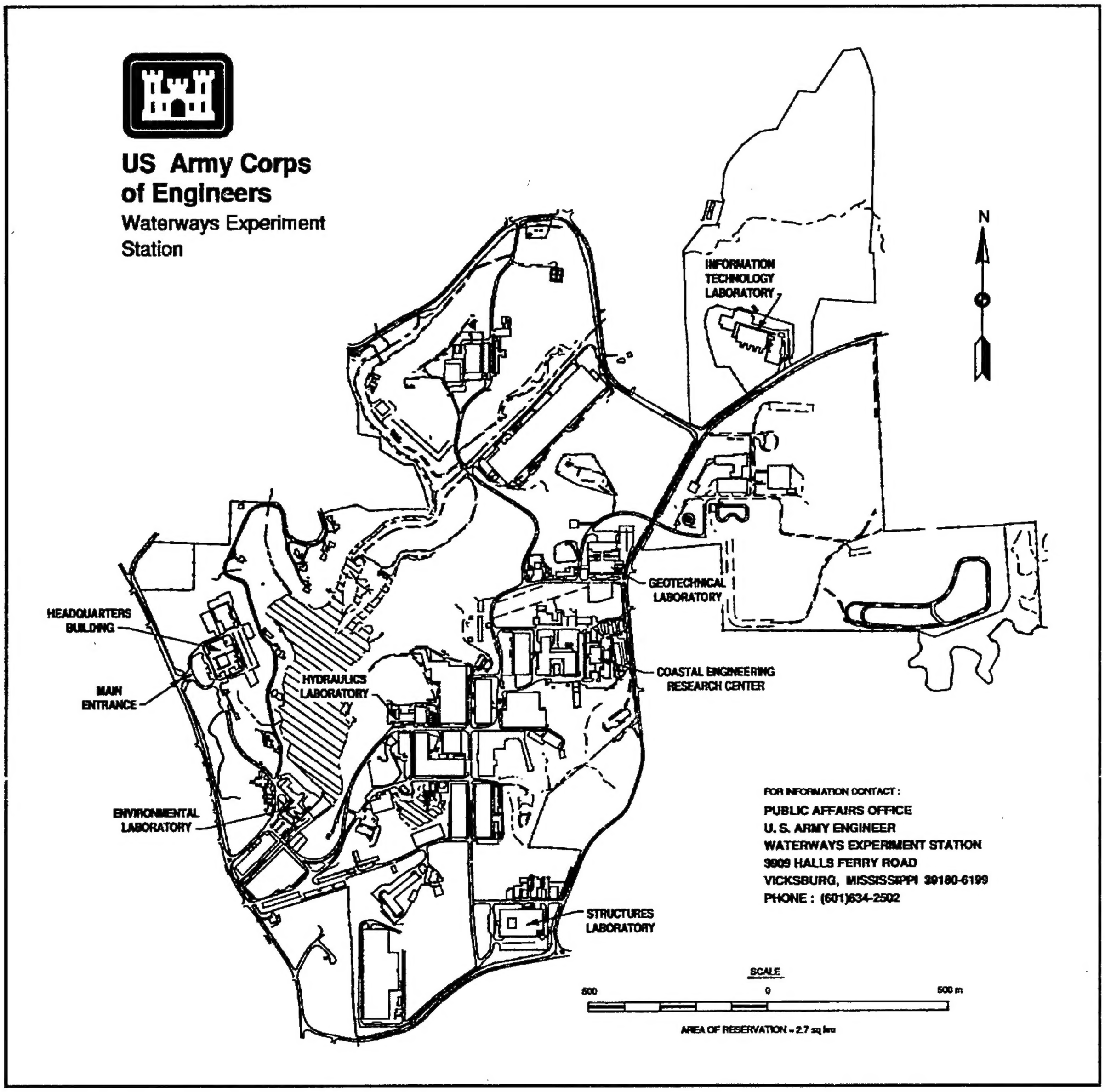

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Contents

Preface

The study reported herein was conducted as part of the Monitoring Completed Coastal Projects (MCCP) Program. Work was carried out under Work Unit 22121, "Periodic Inspections." Overall program management for the MCCP is accomplished by the Hydraulic Design Section of Headquarters, U.S. Army Corps of Engineers (HQUSACE). The Coastal Engineering Research Center (CERC), U.S. Army Engineer Waterways Experiment Station (WES), is responsible for technical and data management and support for HQUSACE review and technology transfer. Technical Monitors for the MCCP Program are Messrs. John H. Lockhart, Jr., Barry W. Holliday, and Charles B. Chesnutt (HQUSACE). The Program Manager is Ms. Carolyn M. Holmes (CERC).

This report is the first in a series that will track the long-term structural response of the Nawiliwili Harbor breakwater, Hawaii, to its environment. The information contained in this report was gathered as a result of land and aerial survey work conducted by Sea Engineering, Inc., under contract to the Corps of Engineers, and broken armor unit surveys conducted by Messrs. Robert R. Bottin, Jr., and Larry R. Tolliver; Ms. Holmes (CERC); and Mr. Stanley J. Boc, U.S. Army Engineer Division, Pacific Ocean (CEPOD).

The work was conducted during the period August through October 1995 under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Director and Assistant Director, CERC, and under the direct supervision of Messrs. C. E. Chatham, Jr., Chief, Wave Dynamics Division, and Dennis G. Markle, Chief, Wave Processes Branch, CERC. This report was prepared by Messrs. Bottin, CERC, and Boc, CEPOD.

Director of WES during the investigation and publication of this report was Dr. Robert W. Whalin. WES Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in figures, plates, and tables of this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	30.48	centimeters
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Work Unit Objective and Monitoring Approach

The objective of the Periodic Inspections work unit in the Monitoring Completed Coastal Projects (MCCP) research program is to periodically monitor selected coastal navigation structures to gain an understanding of the long-term structural response of unique structures to their environment. These periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed coastal navigation projects. These data also will help avoid repeating past design mistakes that have resulted in structure failure and/or high maintenance costs. Past projects monitored under the MCCP program, and/or structures with unique design features that may have application at other sites, are considered for inclusion in the periodic inspections monitoring program. Selected sites are presented as candidates for development of a periodic monitoring plan. Those sites receiving favorable response during MCCP program review are inspected and a monitoring plan is developed and presented for approval. Once the monitoring plan for a site is approved by the field review group and funds are provided, monitoring of the site is initiated. Normally, base conditions are established and documented in the initial effort. The site then is reinspected on a periodic basis (frequency of surveys is based on a balance of need and funding for each monitoring site) to obtain long-term structural performance data.

Relatively low-cost remote sensing tools and techniques, with limited ground truthing surveys, are the primary inspection tools used in the monitoring efforts. Most periodic inspections consist of capturing above-water conditions of the structure at periodic intervals using high-resolution aerial photography. A visual comparison of periodic aerial photographs is used to gauge the degree of in-depth analysis required to quantify structural changes (primarily armor unit movement). Data analysis involves using photogrammetric techniques developed for and successfully applied at other coastal sites. At sites where local wave data are being gathered by other projects and/or agencies and acquisition of these data can be made at a relatively low cost, wave data are correlated with structural changes. In areas where these data are not available, general observations and/or documentation of major storms occurring in the locality are

presented along with the monitoring data. Ground surveys are limited to the level needed to establish the accuracy of the photogrammetric techniques.

When a coastal structure is photographed at low tide, an accurate permanent record of all visible armor units is obtained. Through the use of stereoscopic, photogrammetric instruments in conjunction with photographs, details of structure geometry can be defined at a point in time. By direct comparison of photographs taken at different times, as well as the photogrammetric data resolved from each set of photographs, geometric changes (i.e. armor unit movement and/or breakage) of the structure can be defined as a function of time. Thus, periodic inspections of the structures will capture permanent data that can be compared and analyzed to determine if structure changes are occurring that indicate possible failure modes and the need to monitor the structure(s) more closely. The Nawiliwili Harbor breakwater, Hawaii, was nominated for periodic monitoring by the U.S. Army Engineer Division, Pacific Ocean (CEPOD).

Two additional CEPOD projects have been monitored previously under the Periodic Inspections work unit. Base conditions have been defined for the Kahului Harbor, Maui, HI, and Laupahoehoe Boat Launching Facility, Hawaii, HI, breakwaters (Markle and Boc 1994).

Project Location and Brief History

Nawiliwili Harbor is located on the southeast coast of the island of Kauai (Figure 1) approximately 185 km (115 miles)[1] northwest of Honolulu, Oahu, HI. The harbor is protected by a 625-m-long (2,050-ft-long) rubble-mound breakwater. The Nawiliwili breakwater protects the inner breakwater of the small-boat harbor, the commercial harbor, and major industries along its waterfront (Figure 2). It is one of the most complex rubble-mound structures the Corps has constructed. The structure was originally armored with keyed-and-fitted stone, and now has several sizes of dolos and tribar concrete armor units. It has a unique rib cap which provides buttressing for the armor and access along its alignment. The structure has had a long history of repair since its original construction was completed in 1922. It has repeatedly been subjected to major storm events, including three hurricanes during its 70-year history.

[1] Units of measurement in the text of this report are shown in SI (metric) units, followed by non-SI (British) units in parentheses. In addition, a table of factors for converting non-SI units of measurement used in figures in this report to SI units is presented on page v.

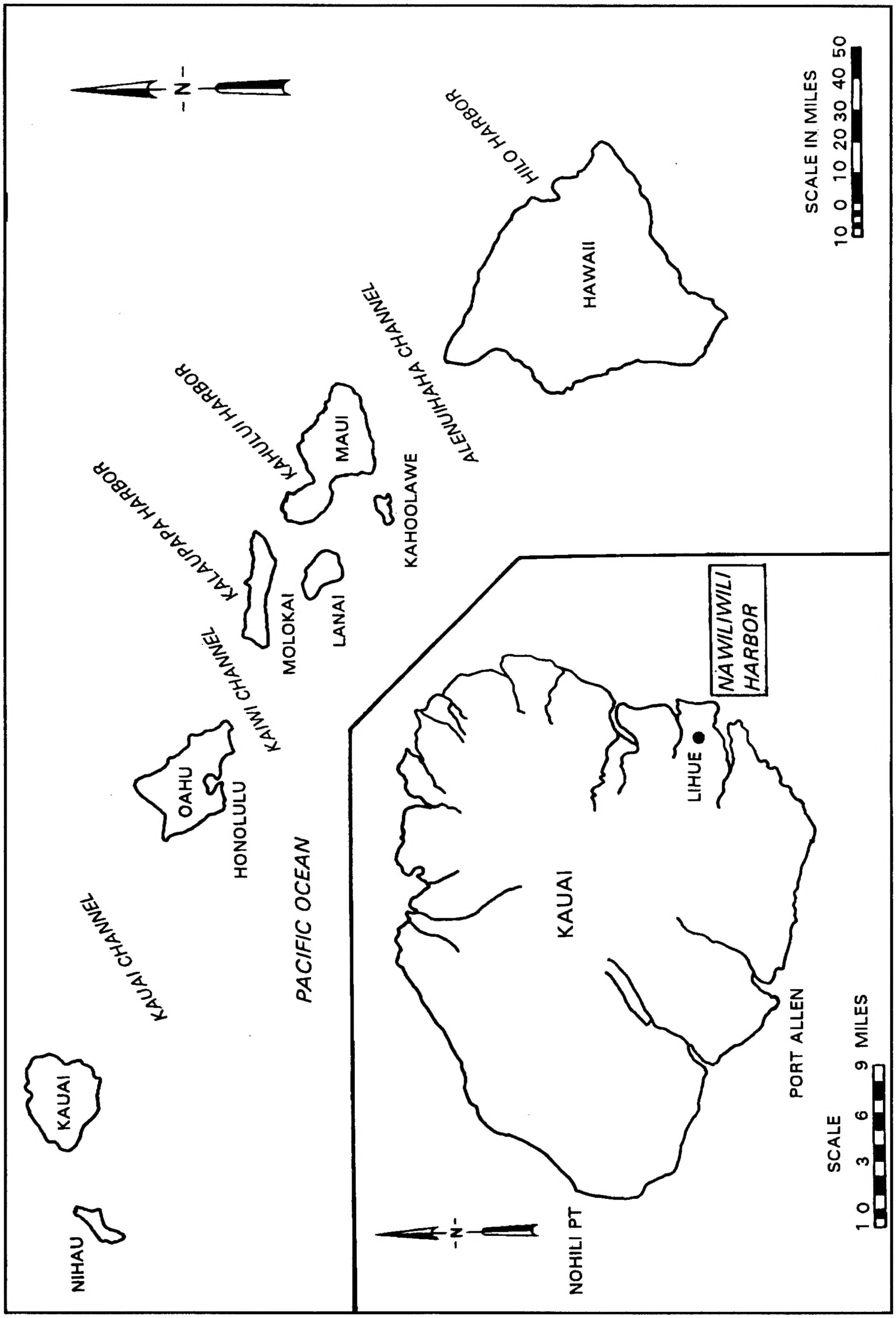

Figure 1. Project location

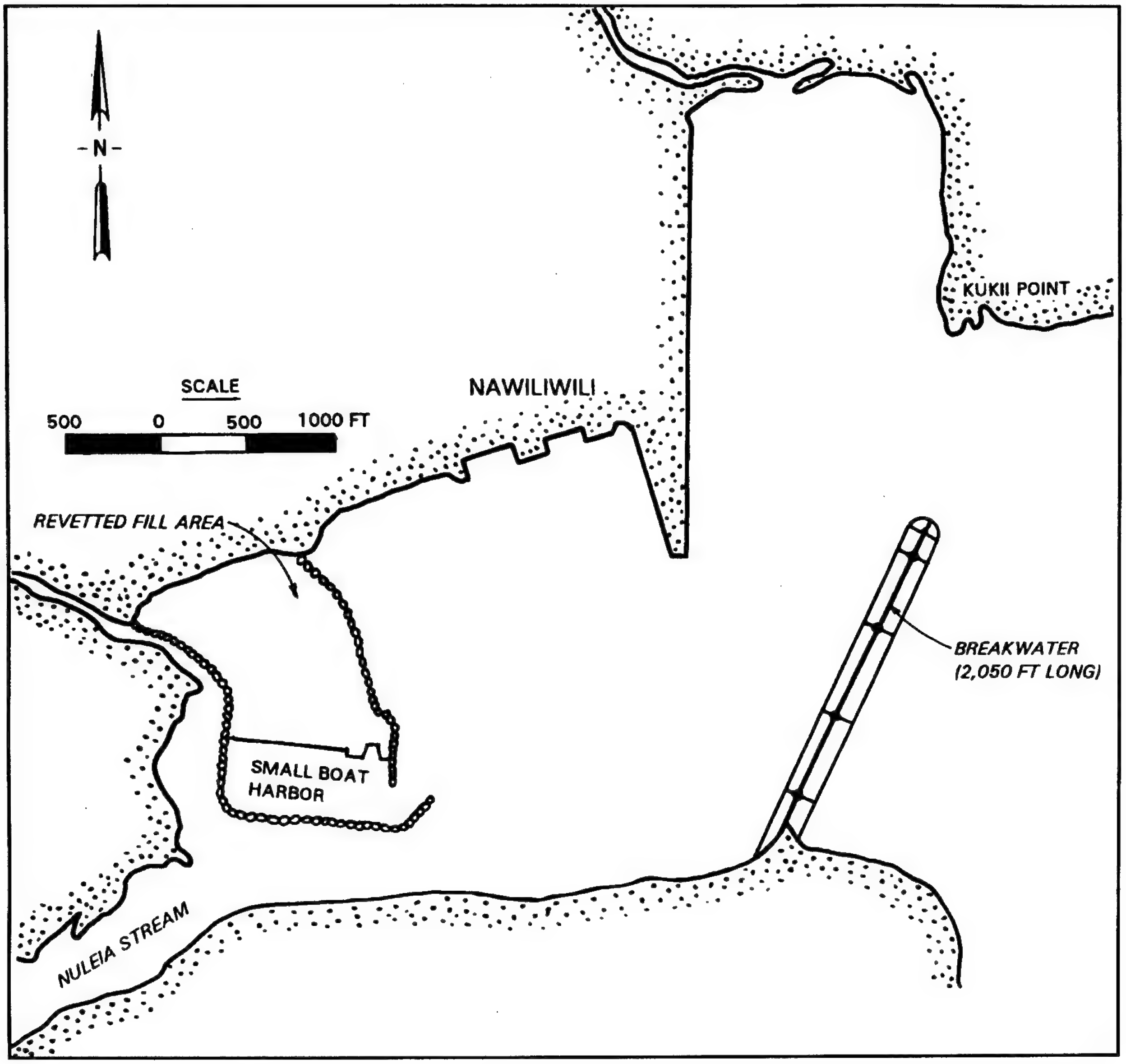

Figure 2. Layout of Nawiliwili Harbor, Hawaii

The breakwater was originally constructed with a single layer of keyed and fitted armor stone placed over quarryrun core stone (227 kg (500 lb) or less). The armor cover on the breakwater consisted of 9,070-kg (10-ton) stone on the crest and seaside slope to an elevation (el) of -0.9 m (-3 ft)[1], 1,814-kg (2-ton) stone on the harbor-side slope from the crest to an el of -0.9 m (-3 ft), and 454-kg (0.5-ton) stone on both the sea-side and harbor-side slopes from the -0.9-m (-3-ft) el to the existing bottom. The breakwater was constructed with a 1V:1H slope on the harbor side and a 1V:1.5 slope on the sea side from the crest to an el of -3.7 m (-12 ft). Below the -3.7-m (-12-ft) el, the sea-side slope was 1V:1H to the existing bottom (Sargent, Markle, and Grace 1988). The breakwater had a 4.6-m

1 All elevations (el) and depths cited herein are in meters (feet) referred to mean lower low water.

(15-ft) crest width with an el of +3.4 m (+11 ft). A cross section of the original structure is shown in Figure 3.

The first major storm damage occurred in 1929, and the slope of the structure was repaired by resetting 114 stones and adding 2,857,600 kg (3,150 tons) of stone and concrete blocks. Between 1930 and 1952, an additional 1,814,370 kg (2,000 tons) of stone were used in repair work on the structure. In 1954, the breakwater again experienced severe storm damage. The head section and approximately 30.5 m (100 ft) of the trunk were destroyed. Severe storms again impacted the breakwater in 1956 and an additional 100-m (330-ft) section of trunk was dèstroyed. The storms of 1954 and 1956, and yet another in 1957, led to the first major rehabilitation of the structure in 1959 (Turk, Melby, and Young 1995).

The 1959 rehabilitation utilized 16,150-kg (17.8-ton) tribar armor units. A two-layer, random placement was used on the head and outer 15.2 m (50 ft) of the structure, and uniformly placed, single layer placement was used along 152 m (500 ft) of trunk on the seaside slope (stas 15+00 - 20+00). A concrete cap also was poured on the crest of the breakwater in 1959 with a crest el of +4.0 m (+13 ft). Typical cross sections for the 1959 repair are shown in Figure 4. The wave height used for design of the armor units for the 1959 rehabilitation was 7.3 m (24 ft). Of the 598 tribars placed, 351 were reinforced. The Corps tagged 150 of the tribars for indicators of movement on the slope during future surveys. After the rehabilitation was completed, Hurricane Dot struck Kauai. It was reported that the structure survived with only minor damage. Three tribars were broken, and some shifting of armor units occurred. Wave heights were estimated as approaching the 7.3-m (24-ft) design wave height.

Due to continued damage to the breakwater, another rehabilitation was initiated in 1977. It consisted of the use of 9,980-kg (11-ton) dolos armor units. Two layers of unreinforced dolosse (485 units) were placed from

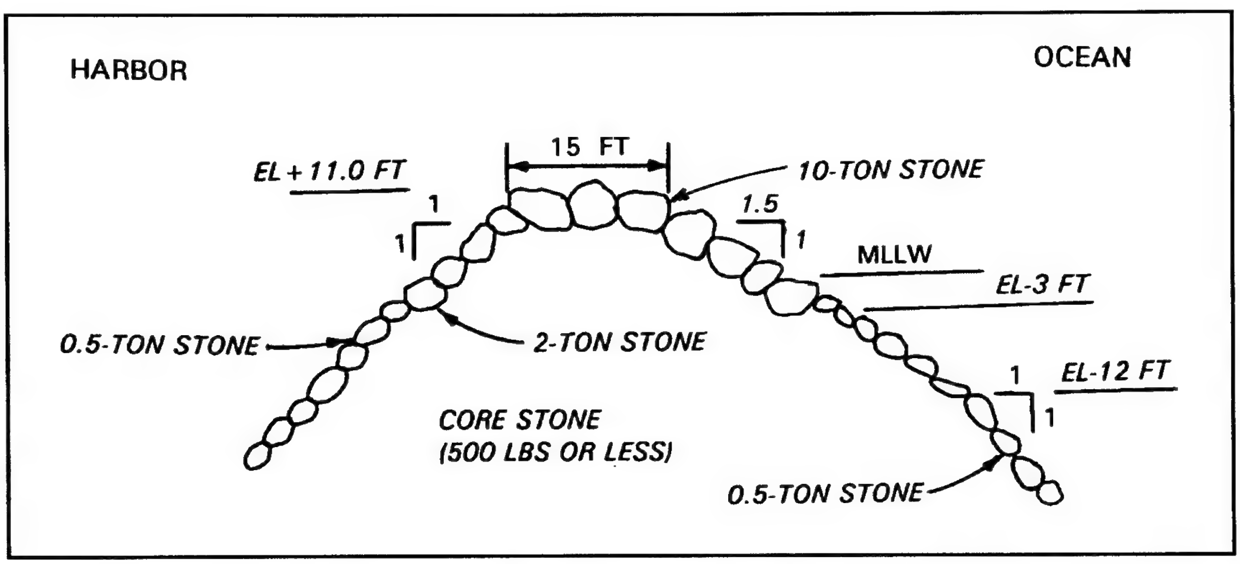

Figure 3. Typical cross section of originally constructed breakwater

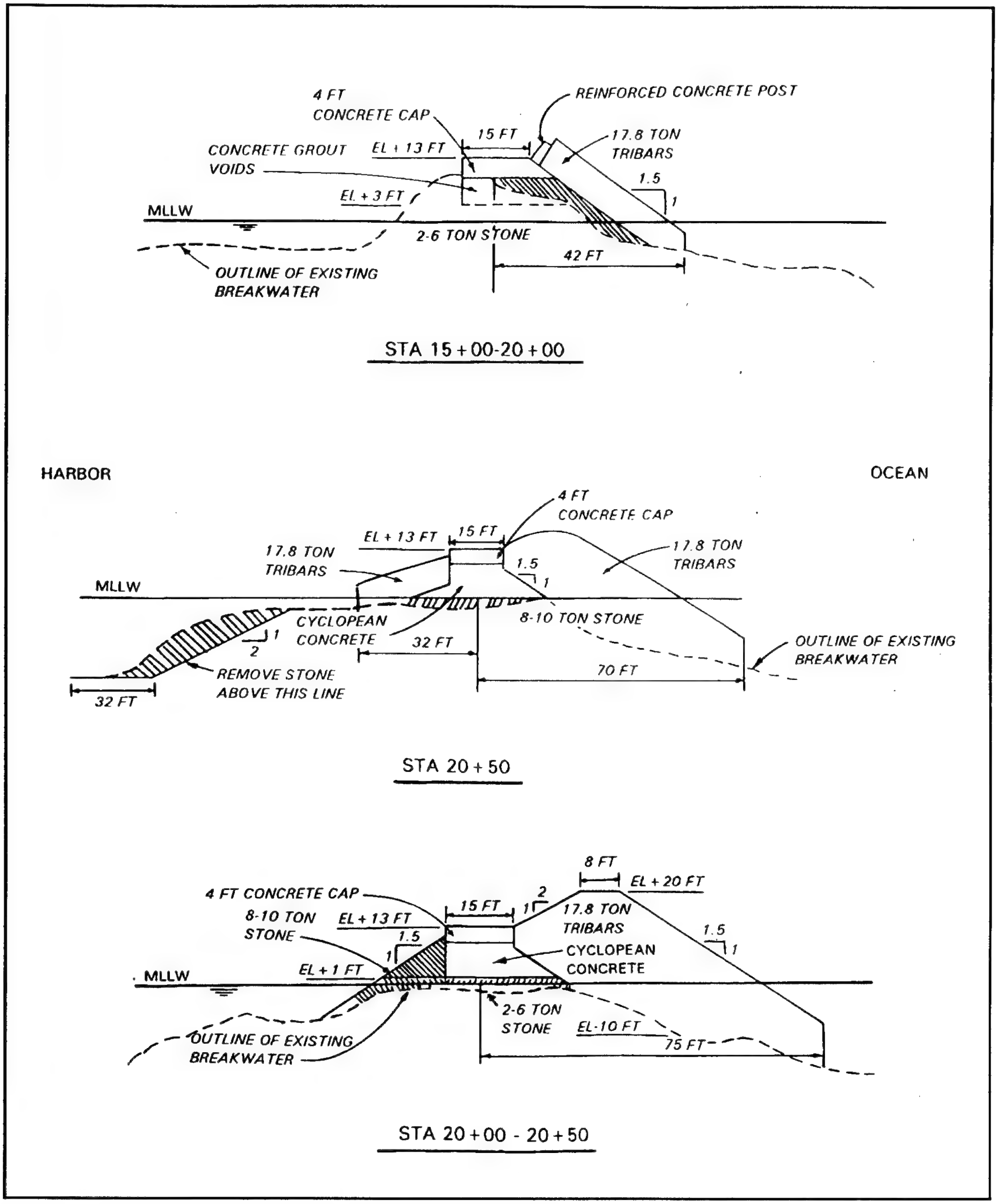

Figure 4. Typical cross sections for 1959 breakwater repairs

the toe to approximately +1.5 m (+5.0 ft) over the one-layer tribar trunk section (stas 15+00 - 20+00). In addition, two layers of dolosse (449 units) were placed from the toe to the crest on the sea-side slope of the trunk for a distance of 91 m (300 ft) shoreward of the tribar area (stas 12+00 - 15+00). Model testing (Davidson 1978) found the dolosse to be hydraulically stable. The seaside slope shoreward of the dolosse (station 5+00 - 12+00) also was repaired with 6,350 - 10,890 kg (7 - 12 ton) stone during the rehabilitation. Cross sections of the 1977 repairs are shown in Figure 5. A breakwater survey conducted in 1980 indicated that the breakwater was in good condition with minimal armor unit breakage observed.

Kauai was devastated by Hurricane Iwa in 1982. Very large waves were reported, and a subsequent inspection revealed nine dolosse and one tribar broken. Movement and shifting of stones on the crest of the structure were noted. A detailed underwater inspection in 1983 found the slope at the structure's head to be approximately 1V:1H, much steeper than the design slope.

In 1987, the breakwater was rehabilitated with 20,865-kg (23-ton) reinforced dolosse (230 units). These units were placed along the steepened head section below the water surface and randomly in low areas around the existing head above the water line. On the harbor-side slope, one layer of 5,900-kg (6.5-ton) tribars was placed along a portion of deteriorated trunk (stas 12+00 - 15+00). These units were model tested (Markle and Herrington 1983) and it was determined that they provided adequate stability. In addition, a 260-m-long (850-ft-long) concrete rib cap was constructed (stas 12+00 - 20+50) to buttress the concrete armor units. Cross sections of the 1987 repairs are shown in Figure 6.

Hurricane Iniki struck the island of Kauai in 1992 with Nawiliwili almost directly in its path. Eyewitness accounts indicated that seas outside the harbor reached 10 m (33 ft) during the storm and over 3 m (10 ft) inside the harbor. Storm surge exceeded 5 m (16 ft) along much of the southern island coast. A survey revealed that three 20,865-kg (23-ton) dolosse, seven 9,980-kg (11-ton) dolosse, and six 16,150-kg (17.8-ton) tribars had broken as a result of the hurricane. A survey of the structure in 1994 revealed a total of 54 broken concrete armor units on the structure above the waterline. An aerial photo of Nawiliwili breakwater in 1995 is shown in Figure 7.

Purpose of the Study

The purposes of the study reported herein were as follows:

a. Develop methods using limited land-based surveying, aerial photography, and photogrammetric analysis to assess the long-term stability response of the concrete armor units on the Nawiliwili breakwater.

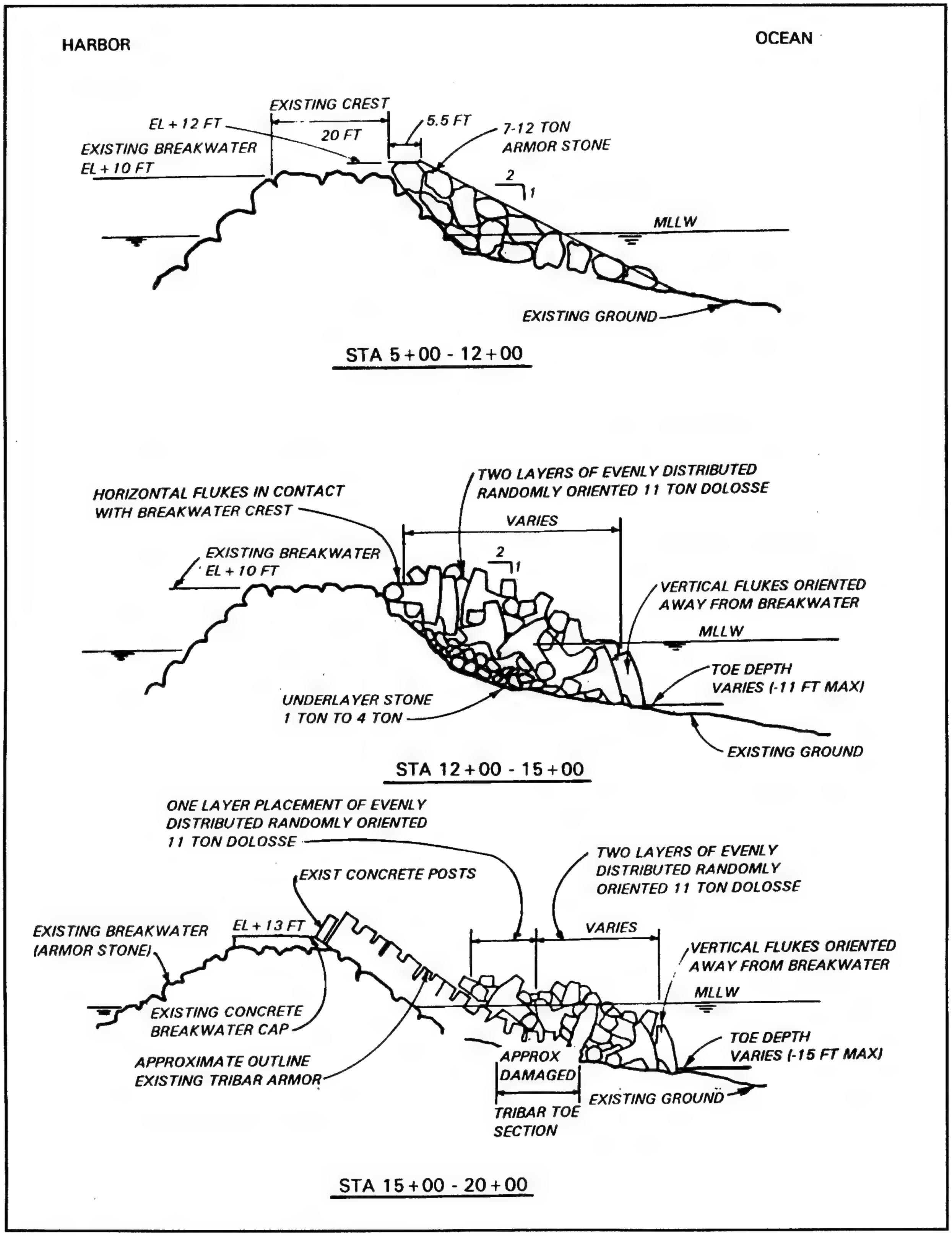

Figure 5. Typical cross sections for 1977 breakwater repairs

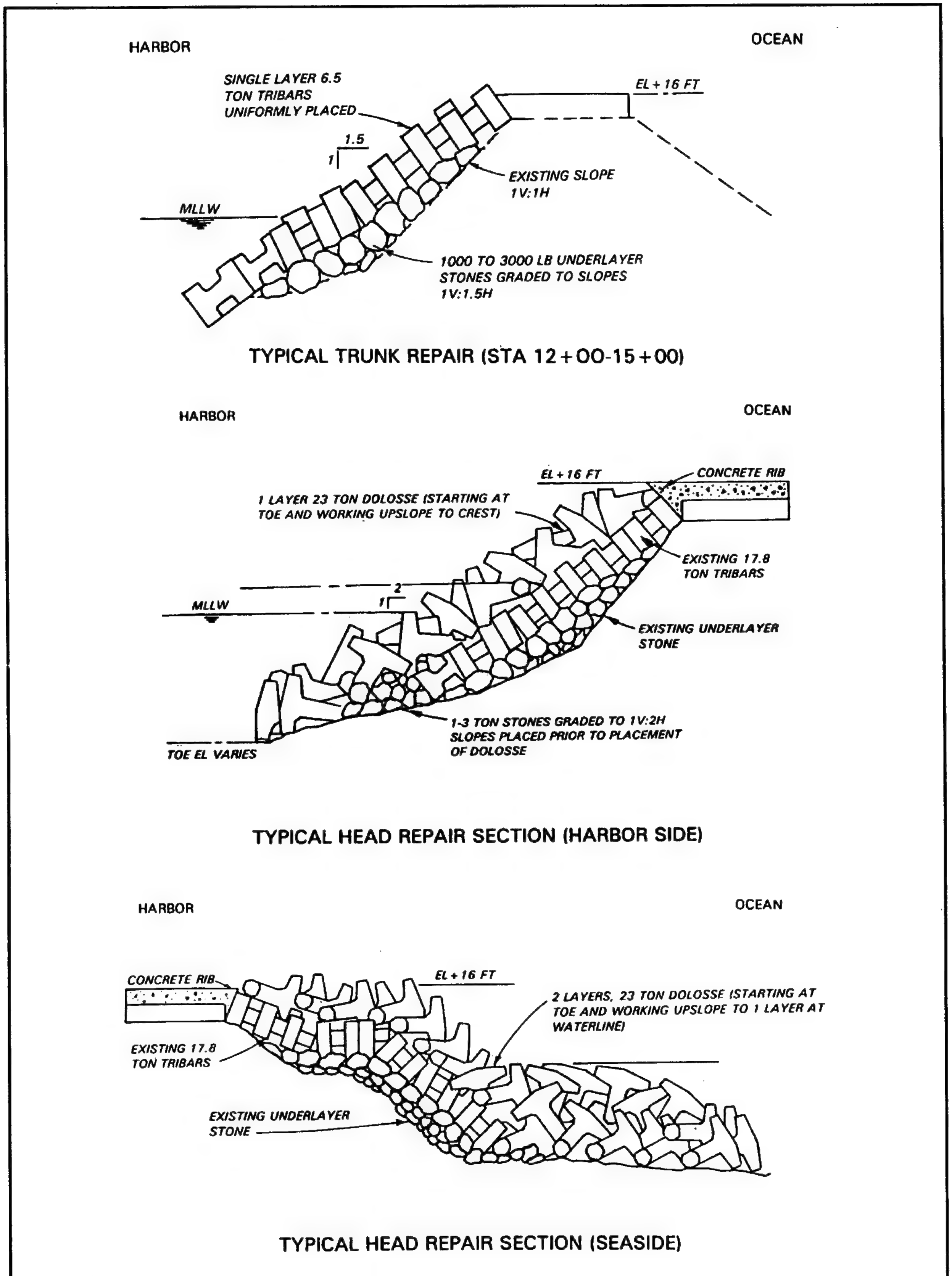

Figure 6. Typical cross sections for 1987 breakwater repairs

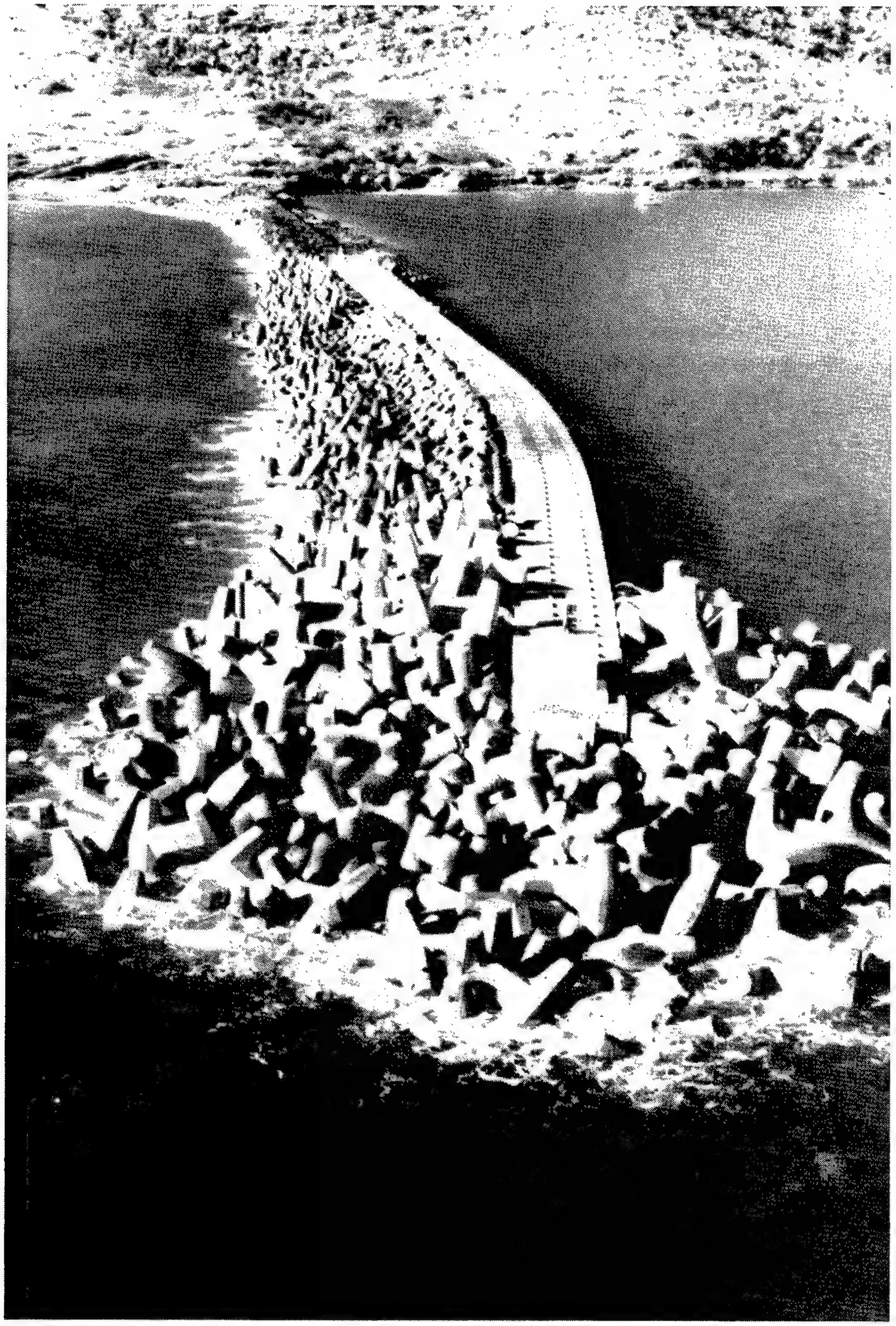

Figure 7. Aerial photograph of Nawiliwili breakwater (1995)

b. Conduct land surveys, broken armor unit inspections, aerial photography, and photogrammetric analyses to:

(1) Test and improve developed methodologies and accurately define armor unit movement above the waterline.

(2) Establish base conditions for the breakwater's armor units which can be revisited in the future under the Periodic Inspections work unit.

2 Monitoring Plan and Data

The objective of the monitoring effort in the Periodic Inspections work unit was to establish base level data upon which long-term stability response of the Nawiliwili Harbor breakwater could be defined through periodic inspections. The concrete armor units on the outer 260-m-long (850-ft-long) portion of the breakwater were monitored. The monitoring plan consisted of targeting and ground surveys, aerial photography, photogrammetric analysis of armor units above the waterline, and ground-based broken armor unit surveys.

Targeting and Ground Surveys

Control points were established on the breakwater to serve as control (both horizontal and vertical reference) for the ground-based survey work as well as the photogrammetric work. Ground surveys were initiated from known monuments on shore. Positions and elevations of the control points established on the structure are shown below and in Figure 8.

Control Point	Easting	Northing	El, m (ft)
HV1	550,399.970	44,743.003	+2.536 (+8.32)
HV2	550,356.010	44,733.344	+4.170 (+13.68)
TR2	550,233.272	44,541.827	+4.852 (+15.92)
HV4	550,192.988	44,367.808	+3.755 (+12.32)
HV5	550,137.082	44,354.828	+4.862 (+15.95)
HV6	550,067.302	44,195.249	+4.852 (+15.92)
TR1	549,986.118	44,001.401	+4.852 (+15.92)
HV7	550,011.927	43,985.472	+2.850 (+9.35)
HV8	549,941.200	44,010.126	+1.481 (+4.86)
HV9	549,921.064	43,884.276	+3.066 (+10.06)

In addition, targets were established on selected concrete armor units to serve as a control to check the accuracy of the photogrammetric work. A total of 21 armor units were selected for targeting, 11 along the sea side of the breakwater trunk and 10 around the breakwater head. Along the trunk,

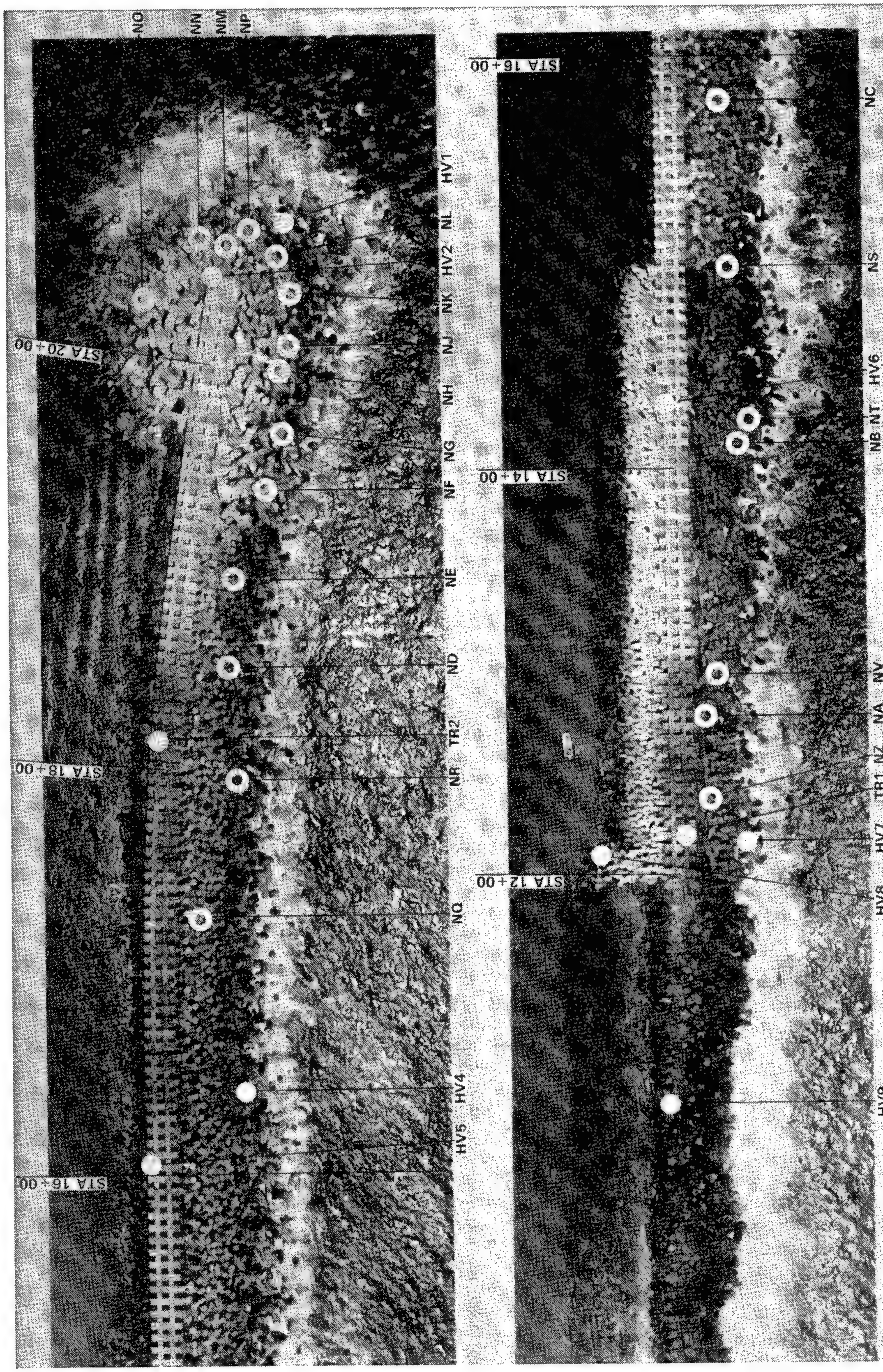

Figure 8. Locations of control points and targeted armor units on Nawiliwili breakwater

9 of the targeted units were 9,980-kg (11-ton) dolos, and two were 16,150-kg (17.8-ton) tribars. Around the head, 5 units were 20,865-kg (23-ton) dolos, and 5 were 16,150-kg (17.8-ton) tribars. Selected units were distributed along the outer 260-m (850-ft) length of the breakwater and from the crest to the waterline. Dolosse and tribars were chosen roughly in proportion to the relative frequency of each unit along a particular length of breakwater. Units were chosen for targeting that had flat surfaces close to horizontal to maximize their visibility in aerial photography and allow for accurate representation of armor unit movement. Figure 8 shows the locations of targeted armor units on the Nawiliwili Harbor breakwater using an identifier of NA, NB, etc.

Each armor unit selected for targeting was painted with three 30.5-cm- (12-in.-) diam targets. The targets were divided into four quadrants which were painted alternately white and black. This style of contrasting target provides a precise center point for which measurements can be made by both land surveys and photogrammetric work. A high-quality epoxy-based marine paint was used to minimize the need for repainting, and a 2.54-cm (1-in.) cross was chiseled at the center of each target for identification in subsequent surveys. Each targeted unit was labeled conspicuously with two 15.2-cm- (6-in.-) high white letters, the first being "N" for Nawiliwili and the second being an identifying letter for the particular unit. Each target on its respective armor unit was identified with a single 15.2-cm (6-in.) white numeral labeled "1" through "3." Examples of targeted armor units are shown in Figures 9 and 10.

Ground surveys of the concrete armor unit targets were conducted on 5-6 September 1995. Target coordinates were established using standard surveying techniques. Horizontal positions were based on the Hawaii State Plane Coordinate System, Zone 1, and elevations were referenced to mean lower low water.

The purpose of armor unit targeting and target surveys was to generate a set of control data by which the accuracy of the photogrammetric survey work could be validated and defined. The ground survey data obtained for the armor unit targets is presented later in this report, where it is compared to the photogrammetric survey data results.

Aerial Photography

Aerial photography is a very effective means of capturing images of large areas for later analysis, study, visual comparison to previous or subsequent photography, or measurement and mapping. Its chief attribute is the ability to freeze a moment in time, while capturing extensive detail.

Aerial photography was obtained along the Nawiliwili breakwater with an aerial mapping camera (9-in. by 9-in. format). Color photos were secured from a fixed-wing aircraft flying at an appropriate altitude, which

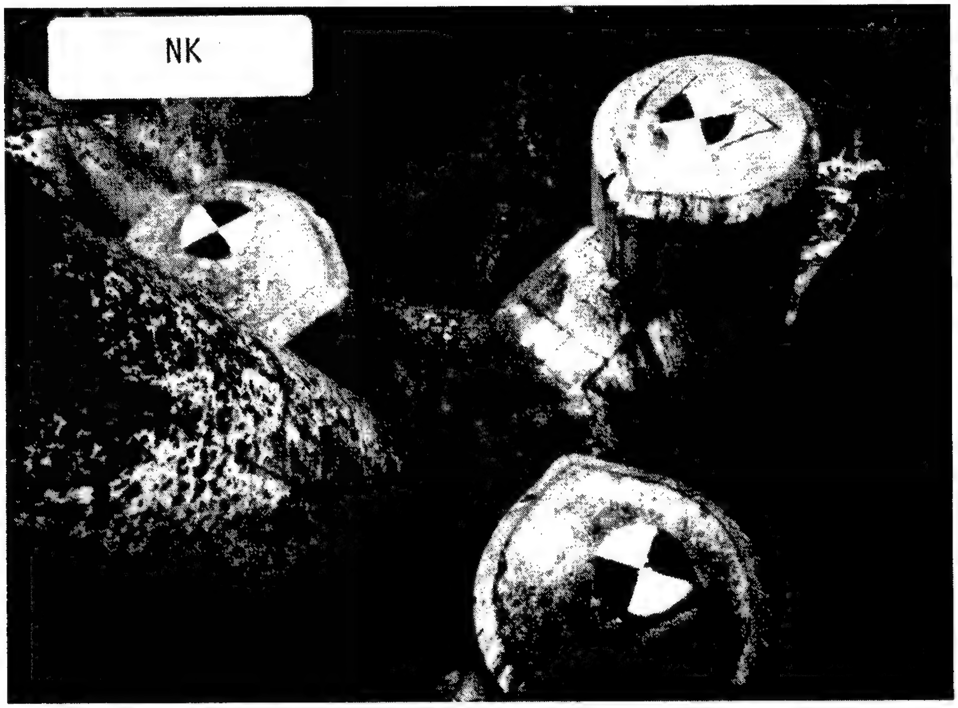

Figure 9. Example of a targeted 17.8-ton tribar

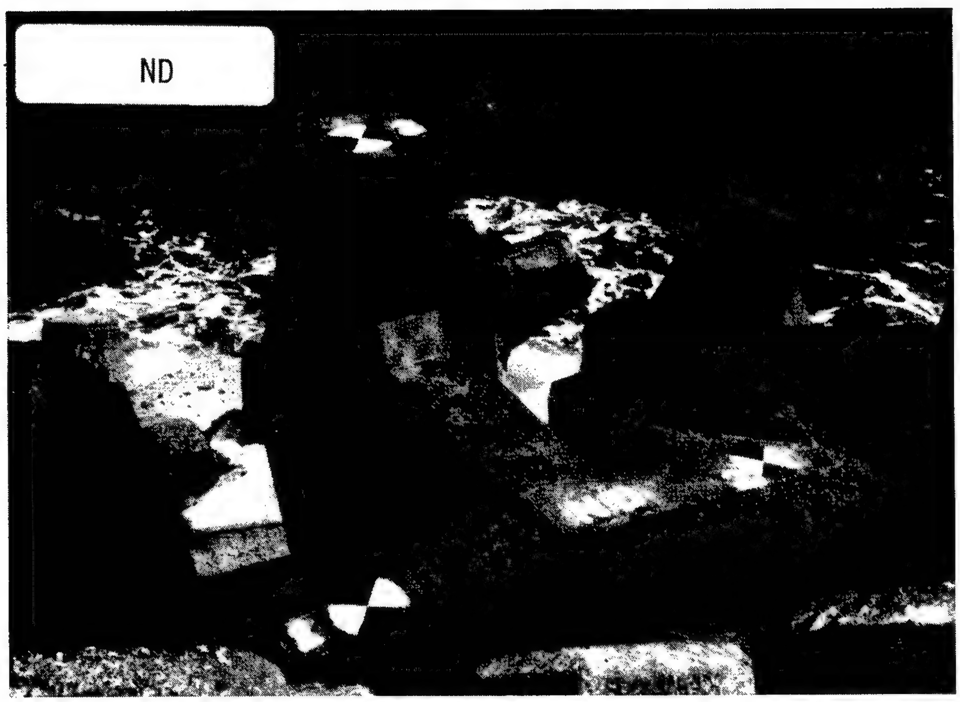

Figure 10. Example of a targeted 11-ton dolos

resulted in high-resolution images and contact prints with scales of 1:1,200. Photographic stereo pairs were obtained during the flights. Stereo pairs secured for the breakwater are shown in Figures 11 and 12. The aerial photography was obtained on 10 September 1995, four days after the ground survey was completed.

Photogrammetric Analysis of Armor Unit Targets

When aerial photography is planned and conducted so that each photo image overlaps the next by 60 percent or more, the two photographs comprising the overlap area can be positioned under an instrument called a stereoscope, and viewed in extremely sharp three-dimensional detail. If properly selected survey points on the ground have previously been targeted and are visible in the overlapping photography, very accurate measurements of any point appearing in the photographs can be obtained. This technique is called photogrammetry.

The stereo pair images obtained during aerial photography at Nawiliwili Harbor were viewed in a Wild BC-3 Analytical Stereoplotter, and stereomodels were oriented to the control point data previously obtained. In the stereomodel, very accurate horizontal and vertical measurements can be made of any point on any armor unit appearing in the print. The stereomodel was used for all photogrammetric compilation and the development of photo maps.

A photogrammetric analysis of the armor unit targets was conducted and x, y, and z (easting, northing, and el) coordinates were obtained. These data were compared to data derived during the ground surveys to establish the accuracy of the photogrammetric work. Ground survey data and aerial survey data are compared in Table 1. The table shows relatively close comparison between ground and aerial survey data. For the majority of the targets, typical differences ranged from 0.012 to 0.021 m (0.04 to 0.07 ft) or less. Maximum differences were 0.172 and 0.122 m (0.565 and 0.40 ft), respectively, for the horizontal and vertical positions; however, this level of difference occurred for only one target for the horizontal and one target for the vertical position. In general, the differences in the horizontal positions were slightly closer than the vertical positions. Ninety-eight percent of all horizontal target positions and eighty-six percent of all vertical target positions were within 0.061 m (0.2 ft).

With the x, y, and z (easting, northing, and el) coordinates defined for each target on the various armor units, the centroid of each targeted armor unit was computed. In addition, the position of each armor unit relative to the x, y, and z axes was determined. Figure 13 shows the orientation of representative armor units to the three axes. The centroid of each targeted armor unit and each unit's orientation (rotation angle relative to x, y, and

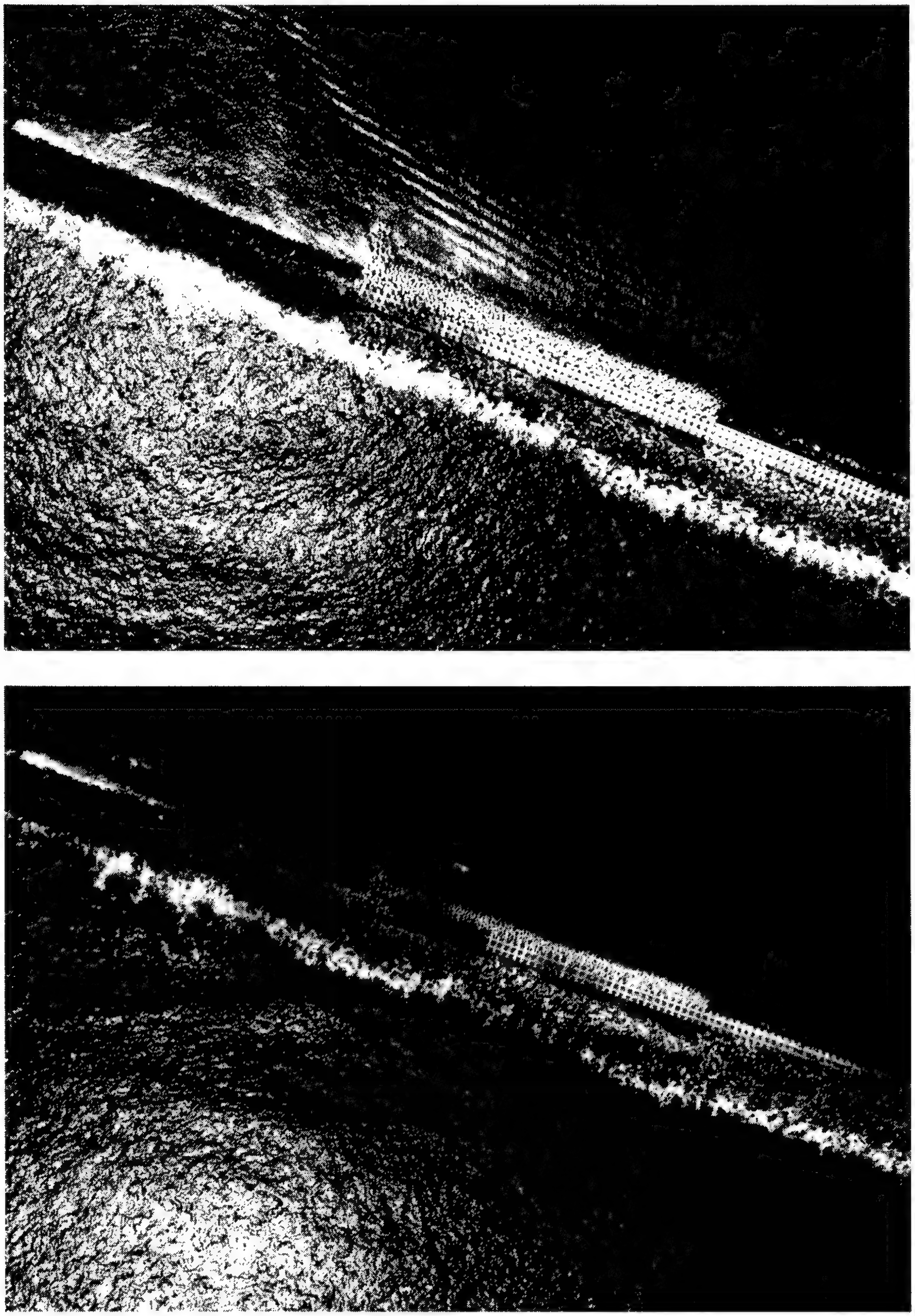

Figure 11. Stereo pair photographs of inner portion of Nawiliwili breakwater

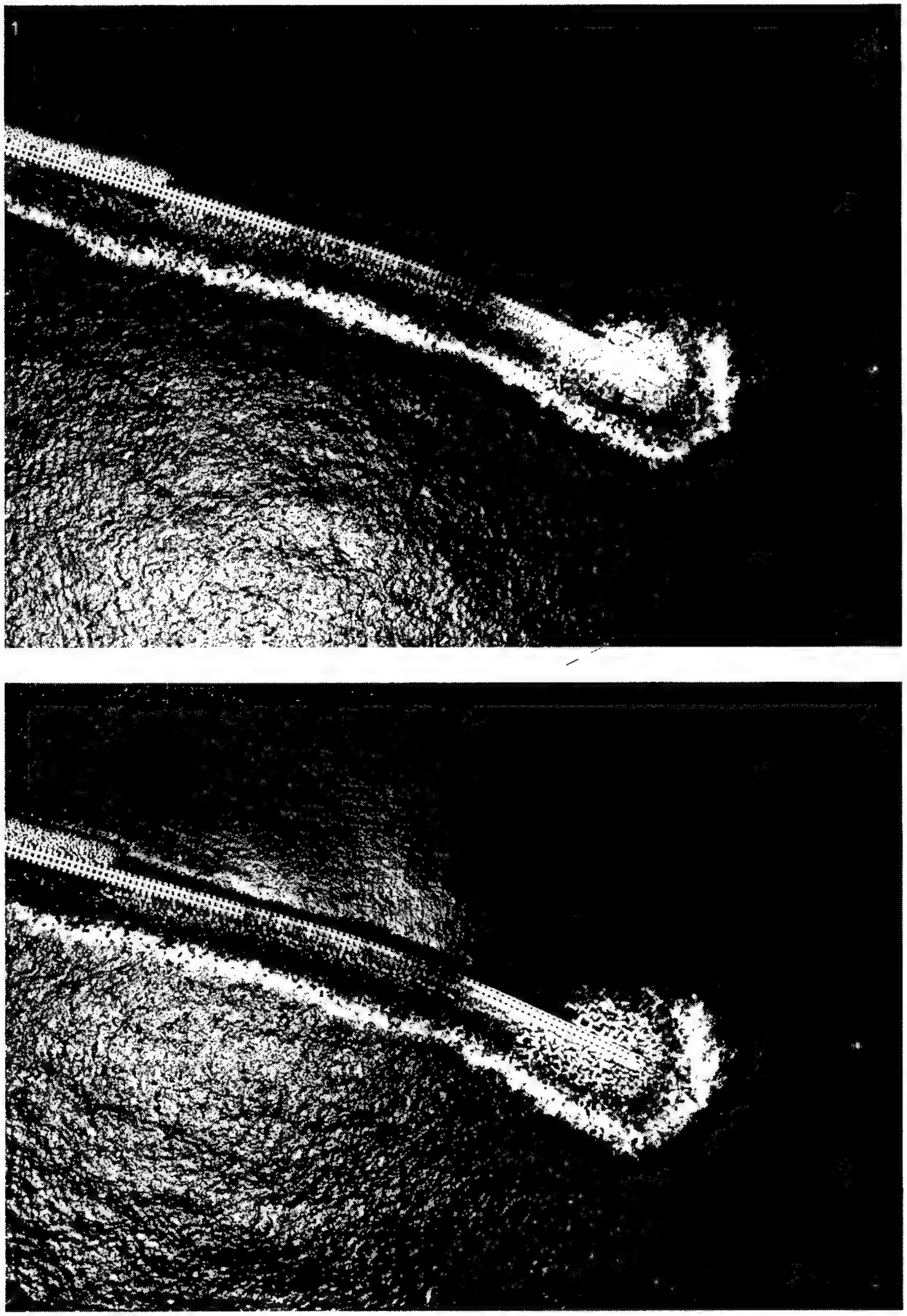

Figure 12. Stereo pair photographs of outer portion of Nawiliwili breakwater

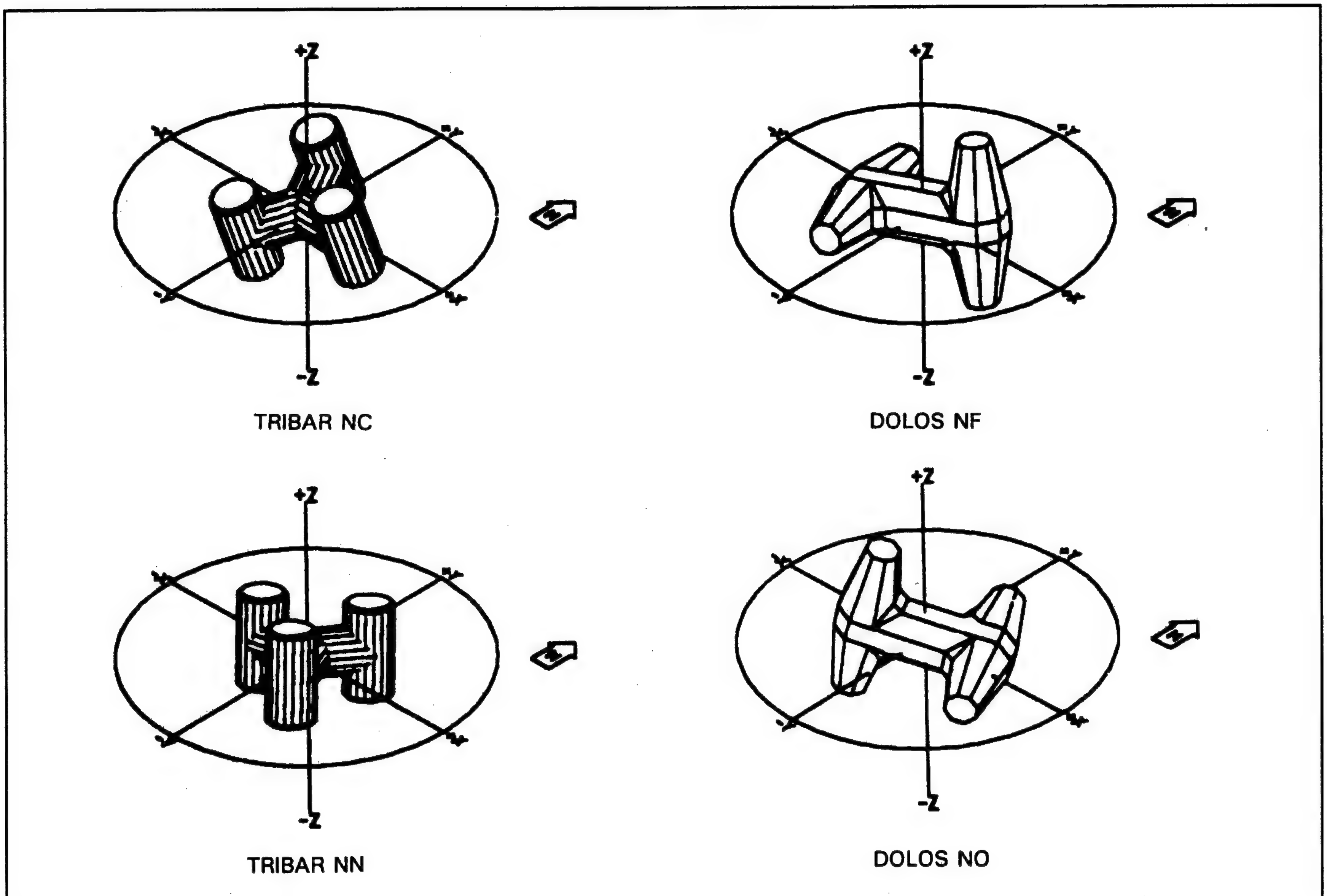

Figure 13. Representative targeted armor unit positions relative to x, y, and z axes

z) are presented in Table 2 for the aerial survey results. These are base level conditions from which comparisons can be made in future surveys.

Photo maps combine the image characteristics of a photograph with the geometric qualities of a map. The image is rectified and free from skewness and distortion, and therefore, precise horizontal measurements may be obtained using an engineer scale. Photo maps were prepared for the outer 260-m (850-ft) length of the Nawiliwili breakwater. They were produced on Mylar sheets at a scale of 1:240.

Full-scale hard copies of aerial photographs and photo maps are on file at the authors' offices at the U.S. Army Engineer Waterways Experiment Station and CEPOD. In addition, all photogrammetric compilations and analyses have been stored on diskettes in AutoCad files for future use. In summary, very detailed and accurate information relative to the armor unit positions for the Nawiliwili Harbor breakwater have been captured by means of aerial photography and photogrammetric analysis. Data are stored and can be retrieved and compared against data obtained during subsequent monitoring. Thus, armor unit movement may continue to be quantified precisely in future years.

Broken Armor Unit Surveys

On 29 August 1995, a survey of broken/cracked armor units above the waterline was conducted on the outer 260-m (850-ft) portion of the Nawiliwili Harbor breakwater. During the inspection, each broken armor unit was identified and photographed, and its approximate location relative to breakwater station and distance from a baseline was recorded. The baseline was the approximate center line of the structure. A total of 61 broken or cracked armor units were identified along the structure during the walking survey. Due to excessive wave action, however, broken/cracked armor units along the water's edge may have been missed, since this portion of the structure was inaccessible by foot. On 6 September 1995, an aerial survey of broken/cracked armor units was conducted by helicopter. This survey identified 39 broken or cracked armor units along the structure. Photographs and locations of these damaged units were recorded. Many of these armor units were duplicates of those obtained during the walking survey. After evaluating the data from the two surveys, it was determined that 70 broken/cracked armor units existed on the structure. The helicopter survey identified nine additional units along the water's edge that were not recorded during the walking survey.

The approximate locations of broken/cracked armor units along the outer portion of the breakwater are shown in Figure 14, and detailed data obtained during the broken armor unit inventory are shown in Table 3. Armor unit numbers identified in Figure 14 correspond to those listed in Table 3. As shown, broken units occur along the entire length on the sea side of the structure, but in general, are more concentrated along the

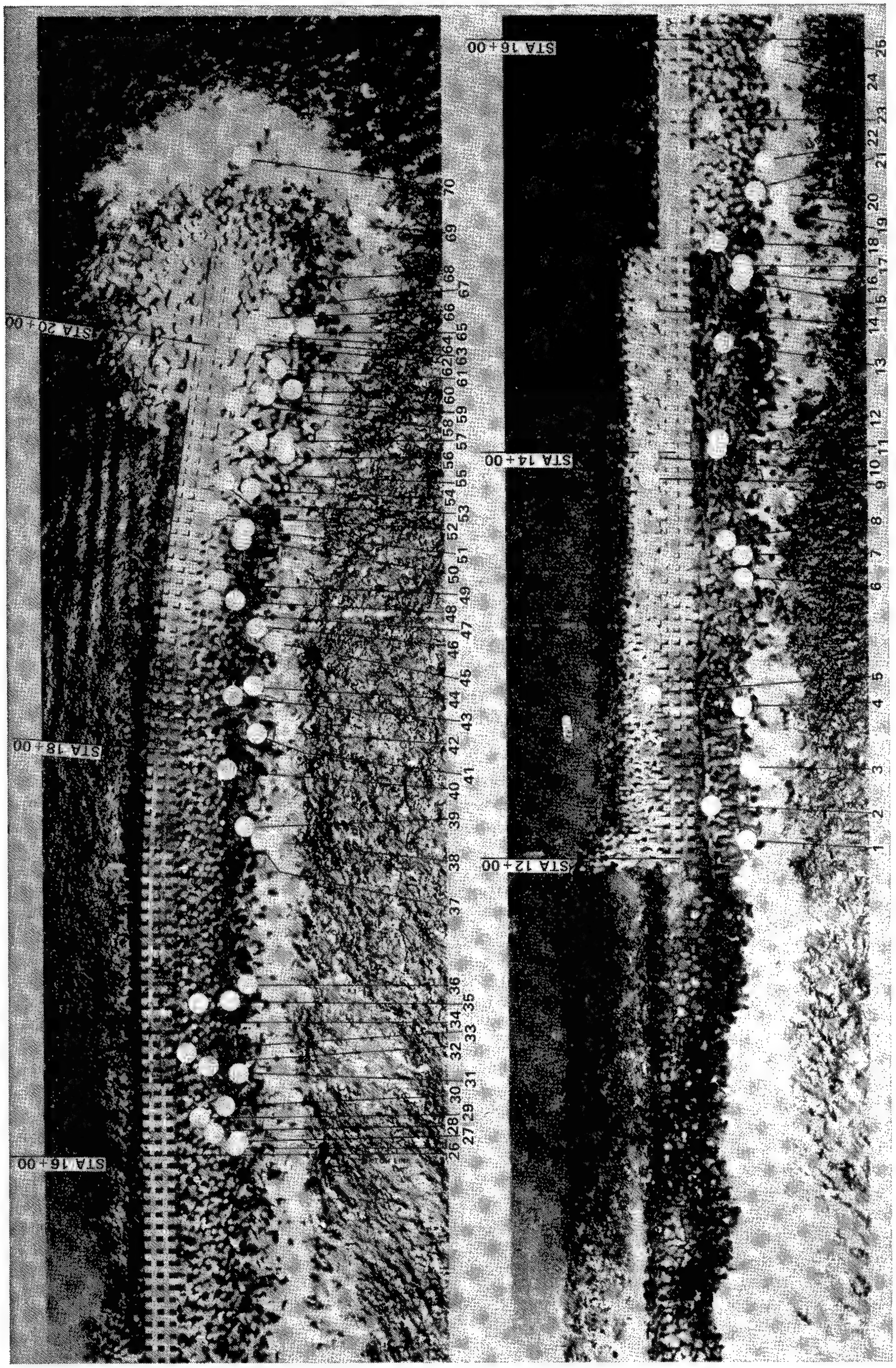

Figure 14. Approximate locations of broken/cracked armor units along outer portion of Nawiliwili Harbor breakwater

seaward end of the breakwater. Sixty-one percent of the broken units are located on the outer half of the structure (sta 16+00 - 20-50), and about one third of the broken units are situated on the outer 45.7-m (150-ft) length of the breakwater (sta 19+00 - 20+50). With regard to distance from baseline, the majority of broken units (71 percent) are located between 7.6 and 16.8 m (25 and 55 ft) seaward of the baseline. These units are in the active wave zone.

Types of breaks for the dolosse included shank and fluke breaks. These were characterized as mid-shank, shank-fluke (shank broken in vicinity of fluke), and fluke-shank (fluke broken off at junction with shank). Also recorded were straight breaks (broken straight across) and angled breaks (broken at some angle to the dolos limb). For the tribars, types of breaks included those through the center section of the unit where one or more legs were separated from the unit, and those in which just a portion of one of the legs was broken off. Views of representative types of breaks for the armor units are shown in Figures 15-18. Armor units with hairline cracks on one side were not counted; only those that were cracked all the way through were considered a break for recording purposes.

Of the 70 broken or cracked armor units, 39 were 9,980-kg (11-ton) dolosse, 19 were 16,150-kg (17.8-ton) tribars, 8 were 20,865-kg (23-ton) dolosse, and 4 were 5,900-kg (6.5-ton) tribars. Considering the types of breaks, 54 percent (21 units) of the 9,980-kg (11-ton) dolosse and 63 percent (5 units) of the 20,865-kg (23-ton) dolosse were determined to be mid-shank breaks. Of all the dolosse breaks recorded, 77 percent were straight and 23 percent were angled. Of the 19 broken 16,150-kg (17.8-ton) tribars, 14 (74 percent) consisted of one leg broken off through the center of the unit. The four broken 5,900-kg (6.5-ton) tribars on the harbor side of the breakwater appeared to have been placed in that condition. They seemed to have been fitted on the crest adjacent to the rib cap. The detailed data obtained during the broken armor unit survey will allow for an accurate indication of new breaks when the structure is revisited at some point in the future.

Figure 15. Dolos with mid-shank break

Figure 16. Dolos with fluke-shank break

Figure 17. Dolos with shank-fluke break

Figure 18. Tribar with break through center section of unit

3 Summary

The Nawiliwili Harbor breakwater has been repeatedly subjected to major storm events, including three hurricanes, during its 70-year history. As a result, extensive breakwater damage has occurred. Major rehabilitations were completed in 1959, 1977, and 1987. The structure was originally armored with keyed-and-fitted stone, but now has several sizes of tribar and dolos concrete armor units. The Nawiliwili breakwater is one of the most complex rubble-mound structures the Corps of Engineers has constructed. No sound, quantifiable data relative to the movement or positions of the concrete armor units had been obtained for the structure prior to this study.

Under the current Periodic Inspections work unit of the Monitoring Completed Coastal Projects Program, data from limited ground-based surveys, aerial photography, and photogrammetric analysis have been obtained to establish very precise base level conditions for the Nawiliwili Harbor breakwater. Accuracy of the photogrammetric analysis was validated and defined through comparison of ground and aerial survey data on control points and targets established on the structure. A method of high-resolution, stereo aerial photographs, a stereoplotter, and AutoCad-based software has been developed to analyze the entire above-water armor unit fields and quantify armor positions and subsequent movement. A detailed broken armor unit survey conducted during the current effort has resulted in a well-documented data set that can be compared to subsequent survey data.

Now that base (control) conditions have been defined at a point in time, and methodology has been developed to closely compare subsequent years of high-resolution data for the Nawiliwili Harbor breakwater, the site will be revisited in the future under the Periodic Inspections work unit to gather data by which assessments can be made on the long-term response of the structure to its environment. The insight gathered from these efforts will allow engineering decisions to be made, based on sound data, as to whether or not closer surveillance and/or repair of the structure might be required to reduce its chances of failing catastrophically. Also, the periodic inspection methods developed and validated for these structures may be used to gain insight into other Corps' structures.

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Table 1
Comparison of Ground and Aerial Surveys of Armor Unit Targets

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
NA1	550021.107	44054.204	+3.319 (+10.890)	550021.140	44054.230	+3.344 (+10.970)	1.006 (0.033)	0.792 (0.026)	2.438 (0.080)
NA2	550016.513	44048.927	+3.466 (+11.370)	550016.560	44048.920	+3.484 (+11.430)	1.433 (0.047)	0.213 (0.007)	1.829 (0.060)
NA3	550024.332	44047.241	+4.343 (+14.250)	550024.320	44047.250	+4.359 (+14.300)	0.366 (0.012)	0.274 (0.009)	1.524 (0.050)
NB1	550089.005	44168.789	+3.551 (+11.650)	550089.010	44168.830	+3.530 (+11.580)	0.152 (0.005)	1.250 (0.041)	2.134 (0.070)
NB2	550087.379	44163.141	+3.274 (+10.740)	550087.380	44163.110	+3.264 (+10.710)	0.030 (0.001)	0.945 (0.031)	0.914 (0.030)
NB3	550095.147	44163.290	+4.036 (+13.240)	550095.150	44163.260	+4.008 (+13.150)	0.091 (0.003)	0.914 (0.030)	2.743 (0.090)
NC1	550152.390	44323.245	+3.850 (+12.630)	550152.420	44323.280	+3.859 (+12.660)	0.914 (0.030)	1.067 (0.035)	0.914 (0.030)
NC2	550151.108	44316.146	+3.725 (+12.220)	550151.180	44316.220	+3.716 (+12.190)	2.195 (0.072)	2.256 (0.074)	0.914 (0.030)
NC3	550157.664	44319.178	+3.255 (+10.680)	550157.720	44319.230	+3.246 (+10.650)	1.707 (0.056)	1.585 (0.052)	0.914 (0.030)
ND1	550277.992	44561.708	+2.932 (+9.620)	550278.020	44561.870	+2.932 (+9.620)	0.853 (0.028)	4.938 (0.162)	0.0 (0.00)
ND2	550277.266	44554.893	+3.112 (+10.210)	550277.280	44555.040	+3.124 (+10.250)	0.427 (0.014)	4.481 (0.147)	1.219 (0.040)
ND3	550283.419	44558.165	+4.346 (+14.260)	550283.500	44558.330	+4.337 (+14.230)	2.469 (0.081)	5.029 (0.165)	0.914 (0.030)
NE1	550304.060	44596.890	+2.804 (+9.2000)	550304.080	44597.030	+2.801 (+9.190)	0.610 (0.020)	4.267 (0.140)	0.305 (0.010)
NE2	550300.914	44591.891	+2.813 (+9.230)	550300.940	44592.020	+2.780 (+9.120)	0.792 (0.026)	3.932 (0.129)	3.353 (0.110)
NE3	550297.931	44597.583	+4.371 (+14.340)	550297.980	44597.790	+4.340 (+14.240)	1.494 (0.049)	6.309 (0.207)	3.048 (0.100)
NF1	550329.318	44633.665	+3.780 (+12.400)	550329.300	44633.860	+3.761 (+12.340)	0.549 (0.018)	5.944 (0.195)	1.829 (0.060)
NF2	550331.658	44626.383	+3.722 (+12.210)	550331.670	44626.530	+3.700 (+12.140)	0.366 (0.012)	4.481 (0.147)	2.134 (0.070)
NF3	550338.269	44630.840	+5.483 (+17.990)	550338.260	44631.030	+5.480 (+17.980)	0.274 (0.009)	5.791 (0.190)	0.305 (0.010)
NG1	550357.885	44649.735	+3.987 (+13.080)	550357.900	44649.910	+4.017 (+13.180)	0.457 (0.015)	5.334 (0.175)	3.048 (0.100)
NG2	550352.199	44655.084	+3.801 (+12.470)	550352.200	44655.220	+3.770 (+12.370)	0.030 (0.001)	4.145 (0.136)	3.048 (0.100)
NG3	550347.806	44646.726	+4.697 (+15.410)	550347.860	44646.920	+4.676 (+15.340)	1.646 (0.054)	5.913 (0.194)	2.134 (0.070)

(Sheet 1 of 3)

Table 1 (Continued)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
NH1	550366.184	44672.609	+3.688 (+12.100)	550366.180	44672.700	+3.685 (+12.090)	0.122 (0.004)	2.774 (0.091)	0.305 (0.010)
NH2	550367.750	44682.147	+3.712 (+12.180)	550367.810	44682.190	+3.755 (+12.320)	1.829 (0.060)	1.311 (0.043)	4.267 (0.140)
NH3	550358.567	44679.342	+5.002 (+16.410)	550358.540	44679.500	+4.980 (+16.340)	0.823 (0.027)	4.816 (0.158)	2.134 (0.070)
NJ1	550378.091	44691.377	+4.200 (+13.780)	550378.040	44691.400	+4.194 (+13.760)	1.554 (0.051)	0.701 (0.023)	0.610 (0.020)
NJ2	550371.214	44689.532	+3.679 (+12.070)	550371.110	44689.500	+3.639 (+11.940)	3.170 (0.104)	0.975 (0.032)	3.962 (0.130)
NJ3	550374.223	44681.598	+5.121 (+16.800)	550374.180	44681.690	+5.133 (+16.840)	1.311 (0.043)	2.804 (0.092)	1.219 (0.040)
NK1	550385.317	44713.309	+4.014 (+13.170)	550385.270	44713.280	+3.972 (+13.030)	1.433 (0.047)	0.884 (0.029)	4.267 (0.140)
NK2	550384.190	44706.131	+3.740 (+12.270)	550384.110	44706.020	+3.725 (+12.220)	2.438 (0.080)	3.383 (0.111)	1.524 (0.050)
NK3	550390.222	44708.647	+4.267 (+14.000)	550390.160	44708.730	+4.197 (+13.770)	1.890 (0.062)	2.530 (0.083)	7.010 (0.230)
NL1	550388.684	44733.523	+2.981 (+9.780)	550388.600	44733.480	+2.947 (+9.670)	2.560 (0.084)	1.311 (0.043)	3.353 (0.110)
NL2	550384.984	44728.078	+3.463 (+11.360)	550384.880	44728.040	+3.420 (+11.220)	3.170 (0.104)	1.158 (0.038)	4.267 (0.140)
NL3	550391.674	44727.140	+2.755 (+9.040)	550391.580	44727.080	+2.722 (+8.930)	2.865 (0.094)	1.829 (0.060)	3.353 (0.110)
NM1	550370.695	44741.661	+3.146 (+10.320)	550370.620	44741.580	+3.100 (+10.180)	2.286 (0.075)	2.469 (0.081)	4.267 (0.140)
NM2	550370.623	44748.212	+3.008 (+9.870)	550370.540	44748.120	+2.950 (+9.680)	2.530 (0.083)	2.804 (0.092)	5.791 (0.190)
NM3	550364.633	44745.687	+3.417 (+11.210)	550364.550	44745.620	+3.341 (+10.960)	2.530 (0.083)	2.042 (0.067)	7.620 (0.250)
NN1	550360.804	44750.984	+3.292 (+10.800)	550360.710	44750.960	+3.240 (+10.630)	2.865 (0.094)	0.732 (0.024)	5.182 (0.170)
NN2	550360.557	44758.056	+3.182 (+10.440)	550360.470	44757.960	+3.136 (+10.290)	2.652 (0.087)	2.926 (0.096)	4.572 (0.150)
NN3	550355.012	44754.341	+2.865 (+9.400)	550354.970	44754.320	+2.743 (+9.000)	1.280 (0.042)	0.640 (0.021)	12.19 (0.400)
NO1	550323.668	44737.820	+3.557 (+11.670)	550323.690	44737.910	+3.450 (+11.320)	0.671 (0.022)	2.743 (0.090)	10.67 (0.350)
NO2	550319.246	44745.340	+3.213 (+10.540)	550319.280	44745.390	+3.133 (+10.280)	1.036 (0.034)	1.524 (0.050)	7.925 (0.260)
NO3	550313.897	44736.436	+4.273 (+14.020)	550313.880	44736.520	+4.161 (+13.650)	0.518 (0.017)	2.560 (0.084)	11.28 (0.370)

(Sheet 2 of 3)

Table 1 (Concluded)

Target ID	Ground Survey			Aerial Survey			Absolute Value of Difference Between Aerial and Ground Surveys		
	Easting (Eg)	Northing (Ng)	Elevation (Elg), m (ft)	Easting (Ea)	Northing (Na)	Elevation (Ela), m (ft)	Eg-Ea, cm (ft)	Ng-Na, cm (ft)	Elg-Ela, cm (ft)
NP1	550379.505	44744.144	+2.377 (+7.800)	550379.440	44744.100	+2.335 (+7.660)	1.981 (0.065)	1.341 (0.044)	4.267 (0.140)
NP2	550385.504	44747.022	+2.771 (+9.090)	550385.440	44746.980	+2.719 (+8.920)	1.951 (0.064)	1.280 (0.042)	5.182 (0.170)
NP3	550379.895	44749.920	+3.386 (+11.110)	550379.820	44749.870	+3.341 (+10.960)	2.286 (0.075)	1.524 (0.050)	4.572 (0.150)
NQ1	550210.014	44456.036	+4.575 (+15.010)	550210.040	44456.210	+4.511 (+14.800)	0.792 (0.026)	5.304 (0.174)	6.401 (0.210)
NQ2	550211.691	44449.802	+4.295 (+14.090)	550211.700	44449.960	+4.231 (+13.880)	0.274 (0.009)	4.816 (0.158)	6.401 (0.210)
NQ3	550216.216	44454.630	+3.676 (+12.060)	550216.270	44454.790	+3.642 (+11.950)	1.646 (0.054)	4.877 (0.160)	3.353 (0.110)
NR1	550254.854	44508.990	+2.786 (+9.140)	550254.920	44509.190	+2.786 (+9.140)	2.012 (0.066)	0.610 (0.020)	0.0 (0.00)
NR2	550255.726	44502.011	+2.303 (+7.555)	550255.790	44502.130	+2.292 (+7.520)	1.951 (0.064)	3.627 (0.119)	1.067 (0.035)
NR3	550261.006	44505.070	+4.084 (+13.400)	550261.060	44505.260	+4.100 (+13.450)	1.646 (0.054)	5.791 (0.190)	1.524 (0.050)
NS1	550120.346	44246.958	+3.280 (+10.760)	550120.350	44246.920	+3.234 (+10.610)	0.122 (0.004)	1.158 (0.038)	4.572 (0.150)
NS2	550121.456	44241.018	+3.182 (+10.440)	550121.490	44240.990	+3.170 (+10.400)	1.036 (0.034)	0.853 (0.028)	1.219 (0.040)
NS3	550125.949	44243.850	+4.868 (+15.970)	550125.930	44243.850	+4.871 (+15.980)	0.579 (0.019)	0.0 (0.00)	0.305 (0.01)
NT1	550097.798	44175.381	+2.923 (+9.590)	550097.790	44175.380	+2.923 (+9.590)	0.244 (0.008)	0.030 (0.001)	0.0 (0.00)
NT2	550100.464	44168.649	+2.783 (+9.130)	550100.500	44168.660	+2.761 (+9.060)	1.097 (0.036)	0.335 (0.011)	2.134 (0.070)
NT3	550104.159	44173.924	+4.365 (+14.320)	550104.140	44173.910	+4.349 (+14.270)	0.579 (0.019)	0.427 (0.014)	1.524 (0.050)
NV1	550034.945	44069.558	+2.768 (+9.080)	550034.920	44069.590	+2.774 (+9.100)	0.762 (0.025)	0.975 (0.032)	0.610 (0.020)
NV2	550029.910	44067.360	+2.618 (+8.590)	550029.890	44067.340	+2.633 (+8.640)	0.610 (0.020)	0.610 (0.020)	1.524 (0.050)
NV3	550033.711	44062.542	+4.209 (+13.810)	550033.670	44062.540	+4.225 (+13.860)	1.250 (0.041)	0.061 (0.002)	1.524 (0.050)
NZ1	550004.005	44017.165	+3.289 (+10.790)	550004.570	44017.180	+3.304 (+10.840)	17.221 (0.565)	0.457 (0.015)	1.524 (0.050)
NZ2	550001.053	44010.132	+3.225 (+10.580)	550001.030	44010.160	+3.234 (+10.610)	0.701 (0.023)	0.853 (0.028)	0.914 (0.030)
NZ3	550007.516	44011.360	+4.907 (+16.100)	550007.500	44011.400	+4.910 (+16.110)	0.488 (0.016)	1.219 (0.040)	0.305 (0.010)

(Sheet 3 of 3)

Table 2
Centroid Data and Orientations of Targeted Armor Units from Aerial Survey

Armor Unit ID	Centroid Coordinates			Rotation Angle (deg)		
	Easting (X)	Northing (Y)	Elevation (Z), m (ft)	X axis	Y axis	Z axis
NA	550,021.28	44,049.47	2.996 (+9.83)	5.7	3.8	49.2
NB	550,090.92	44,165.00	2.850 (+9.35)	13.6	-8.8	64.6
NC	550,152.76	44,319.89	2.649 (+8.69)	-4.3	16.8	-36.6
ND	550,281.04	44,558.08	2.795 (+9.17)	-7.3	4.3	85.0
NE	550,299.78	44,596.72	2.691 (+8.83)	-13.3	-0.9	-121.1
NF	550,334.91	44,630.25	3.484 (+11.43)	-6.5	-3.9	109.0
NG	550,351.84	44,650.40	3.164 (+10.38)	13.3	-6.4	-43.9
NH	550,363.02	44,678.74	3.234 (+10.61)	4.7	0.0	-99.5
NJ	550,374.35	44,686.09	3.380 (+11.09)	3.1	-13.6	12.3
NK	550,387.03	44,709.53	2.969 (+9.74)	11.1	-6.3	-38.7
NL	550,387.58	44,729.04	2.048 (+6.72)	-18.4	6.0	-63.7
NM	550,368.05	44,745.14	2.131 (+6.99)	0.4	11.2	25.7
NN	550,358.94	44,754.24	2.018 (+6.62)	-9.3	-11.1	30.8
NO	550,318.58	44,739.05	2.637 (+8.65)	12.8	-3.9	-60.5
NP	550,381.49	44,748.19	1.853 (+6.08)	21.5	18.2	-38.2
NQ	550,211.38	44,453.75	3.200 (+10.50)	-3.3	24.0	-11.5
NR	550,259.11	44,506.48	2.335 (+7.66)	-12.9	-13.4	95.5
NS	550,124.46	44,243.90	3.185 (+10.45)	-17.4	-6.6	99.6
NT	550,102.26	44,173.35	2.752 (+9.03)	-11.2	-4.6	112.1
NV	550,033.52	44,065.00	2.545 (+8.35)	-11.4	-13.1	20.3
NZ	550,005.95	44,012.17	3.249 (+10.66)	-14.4	-3.5	64.0

Table 3
Broken Armor Unit Inventory Data

Armor Unit No.	Station No.	Type of Armor Unit	Offset from Center line, m (ft)		Type of Break, Comments
			Seaside	Harborside	
1	12 + 10	9,980-kg (11-ton) Dolos	9.45 (31)		Straight mid-shank break
2	12 + 27	9,980-kg (11-ton) Dolos	4.57 (15)		Straight mid-shank break
3	12 + 46	9,980-kg (11-ton) Dolos	12.19 (40)		Straight mid-shank break
4	12 + 73	9,980-kg (11-ton) Dolos	9.45 (31)		Straight mid-shank break
5	12 + 82	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off through center of unit
6	13 + 38	9,980-kg (11-ton) Dolos	10.36 (34)		Angled fluke-shank break
7	13 + 49	9,980-kg (11-ton) Dolos	10.36 (34)		Straight mid-shank break
8	13 + 57	9,980-kg (11-ton) Dolos	7.62 (25)		Straight fluke-shank break
9	13 + 87	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off - placed as two-leg unit
10	13 + 98	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off - placed as two-leg unit
11	14 + 02	9,980-kg (11-ton) Dolos	6.10 (20)		Angled mid-shank break
12	14 + 04	9,980-kg (11-ton) Dolos	7.62 (25)		Straight mid-shank break
13	14 + 53	9,980-kg (11-ton) Dolos	8.23 (27)		Angled mid-shank break
14	14 + 69	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off - placed as two-leg unit
15	14 + 84	9,980-kg (11-ton) Dolos	10.06 (33)		Straight mid-shank break
16	14 + 89	9,980-kg (11-ton) Dolos	10.06 (33)		Straight mid-shank break
17	14 + 89	9,980-kg (11-ton) Dolos	10.06 (33)		Angled fluke-shank break
18	15 + 02	16,150-kg (17.8-ton) Tribar	6.10 (20)		Leg broken off through center of unit
19	15 + 16	9,980-kg (11-ton) Dolos	16.15 (53)		Straight fluke-shank break
20	15 + 25	9,980-kg (11-ton) Dolos	16.15 (53)		Straight shank-fluke break
21	15 + 26	9,980-kg (11-ton) Dolos	12.19 (40)		Straight mid-shank break
22	15 + 42	9,980-kg (11-ton) Dolos	13.72 (45)		Straight mid-shank break
23	15 + 62	16,150-kg (17.8-ton) Tribar	6.10 (20)		Three legs separated through center of unit
24	15 + 96	9,980-kg (11-ton) Dolos	15.54 (51)		Straight mid-shank break
25	15 + 96	9,980-kg (11-ton) Dolos	15.54 (51)		Angled shank-fluke break
26	16 + 02	9,980-kg (11-ton) Dolos	11.23 (37)		Straight shank-fluke break
27	16 + 02	9,980-kg (11-ton) Dolos	11.23 (37)		Straight mid-shank break
28	16 + 10	9,980-kg (11-ton) Dolos	8.53 (28)		Angled mid-shank break
29	16 + 18	16,150-kg (17.8-ton) Tribar	6.40 (21)		Portion of leg broken off unit
30	16 + 23	9,980-kg (11-ton) Dolos	10.36 (34)		Straight fluke-shank break
31	16 + 41	9,980-kg (11-ton) Dolos	13.11 (43)		Straight fluke-shank break
32	16 + 43	9,980-kg (11-ton) Dolos	7.92 (26)		Straight fluke-shank break
33	16 + 50	16,150-kg (17.8-ton) Tribar	5.79 (19)		Leg broken off unit

(Sheet 1 of 3)

Table 3 (Continued)					
Armor Unit No.	Station N	Type Offsetline, m (ft)	Offset from Center line, m (ft)		Type of Break, Comments
			Seaside	Harborside	
34	16 + 76	16,150-kg (17.8-ton) Tribar	6.40 (21)		Leg cracked through near center of unit
35	16 + 76	9,980-kg (11-ton) Dolos	10.67 (35)		Straight mid-shank break
36	16 + 83	9,980-kg (11-ton) Dolos	13.41 (44)		Straight mid-shank break
37	17 + 58	9,980-kg (11-ton) Dolos	15.85 (52)		Straight mid-shank break
38	17 + 59	9,980-kg (11-ton) Dolos	16.76 (55)		Straight fluke-shank break
39	17 + 62	9,980-kg (11-ton) Dolos	13.72 (45)		Straight mid-shank break
40	17 + 92	9,980-kg (11-ton) Dolos	9.45 (31)		Straight fluke-shank break
41	18 + 10	9,980-kg (11-ton) Dolos	13.72 (45)		Straight fluke-shank break
42	18 + 12	9,980-kg (11-ton) Dolos	18.29 (60)		Angled fluke-shank break
43	18 + 30	9,980-kg (11-ton) Dolos	9.14 (30)		Straight fluke-shank break
44	18 + 35	9,980-kg (11-ton) Dolos	12.50 (41)		Straight shank-fluke break
45	18 + 59	9,980-kg (11-ton) Dolos	15.85 (52)		Straight mid-shank break
46	18 + 65	9,980-kg (11-ton) Dolos	12.19 (40)		Straight mid-shank and straight fluke-shank breaks
47	18 + 77	16,150-kg (17.8-ton) Tribar	8.23 (27)		Only one leg remaining in place
48	18 + 78	16,150-kg (17.8-ton) Tribar	4.88 (16)		Leg broken off unit
49	18 + 85	16,150-kg (17.8-ton) Tribar	5.49 (18)		Leg broken off unit
50	19 + 10	9,980-kg (11-ton) Dolos	8.23 (27)		Straight shank-fluke break
51	19 + 15	9,980-kg (11-ton) Dolos	8.84 (29)		Straight shank-fluke break
52	19 + 20	16,150-kg (17.8-ton) Tribar	4.27 (14)		Leg broken off through center of unit
53	19 + 32	16,150-kg (17.8-ton) Tribar	4.57 (15)		Leg broken off through center of unit
54	19 + 34	16,150-kg (17.8-ton) Tribar	8.53 (28)		Leg broken off unit
55	19 + 52	16,150-kg (17.8-ton) Tribar	8.53 (28)		Leg cracked through center of unit
56	19 + 56	20,865-kg (23-ton) Dolos	12.80 (42)		Angled mid-shank break
57	19 + 57	20,865-kg (23-ton) Dolos	12.50 (41)		Straight fluke-shank break
58	19 + 74	16,150-kg (17.8-ton) Tribar	4.27 (14)		Leg broken off unit
59	19 + 79	20,865-kg (23-ton) Dolos	8.53 (28)		Angled mid-shank break
60	19 + 82	20,865-kg (23-ton) Dolos	12.50 (41)		Straight mid-shank break
61	19 + 91	20,865-kg (23-ton) Dolos	9.75 (32)		Straight mid-shank crack
62	20 + 03	16,150-kg (17.8-ton) Tribar	4.57 (15)		Two legs separated from unit
63	20 + 11	16,150-kg (17.8-ton) Tribar	7.32 (24)		Leg broken off unit
64	20 + 11	16,150-kg (17.8-ton) Tribar	9.75 (32)		Leg broken off unit
65	20 + 13	20,865-kg (23-ton) Dolos	13.10 (43)		Angled mid-shank crack
66	20 + 13	16,150-kg (17.8-ton) Tribar	5.79 (19)		Leg broken off unit

(Sheet 2 of 3)

Table 3 (Continued)					
Armor Unit No.	Station No.	Type of Armor Unit	Offset from Center line, m (ft)		Type of Break, Comments
			Seaside	Harborside	
67	20 + 20	16,150-kg (17.8-ton) Tribar	7.01 (23)		Leg broken off unit through center
68	20 + 34	16,150-kg (17.8-ton) Tribar	8.23 (27)		Leg cracked
69	20 + 67	20,865-kg (23-ton) Dolos	18.60 (61)		Angled mid-shank break
70	20 + 90	20,865-kg (23-ton) Dolos	0.0	0.0	Straight shank-fluke crack

(Sheet 3 of 3)

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13. ABSTRACT *(Maximum 200 words)*

Selected coastal navigation structures are periodically monitored under the Periodic Inspections work unit of the Monitoring Completed Coastal Projects research program. Such monitoring is done to gain an understanding of the long-term structural response of unique structures to their environment. Periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed coastal navigation projects.

The Nawiliwili Harbor breakwater, Hawaii, was nominated for periodic monitoring by the U.S. Army Engineer Division, Pacific Ocean. The objective of the monitoring effort was to establish base level data upon which long-term stability response of the Nawiliwili breakwater could be defined through periodic inspections. The concrete armor units on the outer portion of the breakwater were monitored. The monitoring plan consisted of targeting and ground surveys, aerial photography, photogrammetric analysis of armor units above the waterline, and ground-based broken armor unit surveys.

The Nawiliwili site will be revisited in the future to gather data for assessing the long-term response of the structure to its environment. These data will facilitate engineering decisions concerning whether or not closer surveillance and/or repair of the structure might be required to reduce its chances of failing catastrophically. The periodic inspection methods developed and validated for the Nawiliwili breakwater may also be used to gain insight into other Corps structures.

14. SUBJECT TERMS

Aerial photography	Dolosse	Photogrammetry
Breakwaters	Nawiliwili Harbor, Kauai, HI	Remote Sensing
Concrete armor units	Periodic Inspections	Tribars

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